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Performance of MET reconstruction in CMS

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Abstract. The performance of missing transverse momentum reconstruction algorithms is presented using 8 TeV pp collision data collected with the CMS detector, corresponding to an integrated luminosity up to 19.7 fb^{-1} . The resolution of missing transverse momentum, including the effects of pileup interactions and advanced reconstruction algorithms, are measured using events with an identified Z boson or isolated photon.

1. Introduction

The Compact Muon Solenoid (CMS) detector [1] can detect most species of stable particles produced in proton-proton collisions delivered by the Large Hadron Collider (LHC). Notable exceptions are neutrinos and hypothetical neutral weakly interacting particles. Although these particles do not leave a signal in the detector, their presence can be inferred from the momentum imbalance in the plane perpendicular to the beam direction, known as missing transverse momentum and denoted by $\vec{\cancel{E}}_T$. Its magnitude is denoted by \cancel{E}_T and is referred to as missing transverse energy (MET).

Missing transverse momentum plays a critical role in many physics analyses at the LHC. It is a key variable in many searches for physics beyond the standard model, such as supersymmetry and extra dimensions as well as for collider dark matter searches. It also played an important role in studies contributing to the discovery of a new boson at a mass of around 125 GeV, in particular in channels with the WW and $\tau\tau$ final states [2]. In addition, the precise measurement of $\vec{\cancel{E}}_T$ is critical for measurements of standard model physics involving W bosons and top quarks.

The $\vec{\cancel{E}}_T$ reconstruction is sensitive to detector malfunctions and various reconstruction effects resulting in particle momentum mismeasurements and particle misidentification. Precise calibration of all reconstructed physics objects is crucial for the $\vec{\cancel{E}}_T$ performance, and $\vec{\cancel{E}}_T$ is particularly sensitive to multiple proton-proton interactions in the same, earlier, and later bunch crossings (pileup interactions). Thus, it is essential to study $\vec{\cancel{E}}_T$ reconstruction in detail with data.

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL), and the brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. A more detailed description of the CMS detector can be found in Ref. [1].



2. Data samples, particle reconstruction and event selection

The data samples used for studies presented in this paper were collected from February through December 2012 in proton-proton collisions at a centre-of-mass energy $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 19.7 ± 0.5 fb $^{-1}$.

CMS uses global event reconstruction, also called particle-flow (PF) event reconstruction [3], which consists of reconstructing and identifying each particle with an optimized combination of all subdetector information. For each event, hadronic jets are clustered from these reconstructed particles with the infrared and collinear safe anti- k_t algorithm, operated with a size parameter R of 0.5. The collision data are compared to samples of simulated events that are generated either using PYTHIA 6 [4], or MADGRAPH 5 [5] simulation programs. The generated events are passed through the GEANT4-based CMS detector simulation. The simulated events are weighted such that the distribution of the simulated pileup interaction multiplicity matches the expected distribution, as based on measurements of the instantaneous luminosities in data.

The $Z \rightarrow \ell^+ \ell^-$ events, where ℓ is either a muon or an electron, are used in the \cancel{E}_T resolution studies. In order to discriminate between prompt leptons and leptons which were produced inside a jet through decay of a hadron we quantify the isolation of the candidate particle by combining the transverse momenta of all other reconstructed particles inside a cone of $\Delta R < 0.3$ around the particles trajectory. Events with an invariant mass of the dimuon or dielectron system outside of the Z mass window $60 < m(\ell\ell) < 120$ GeV are rejected.

The $W \rightarrow e\nu$ are required to contain one well-identified, isolated electron satisfying $p_T > 30$ GeV and $|\eta| < 2.5$. Events with an additional electron passing the loose working point are vetoed if the additional electron also satisfies $p_T > 20$ GeV and $|\eta| < 2.5$.

In the semi-leptonic $t\bar{t}$ channel, we select single muon and single electron events from the full 2012 CMS dataset. Each event is required to pass either an e+jet or μ +jet trigger. We require at least 2 b-tagged jets with $p_T > 45$ GeV, at least 3 jets with $p_T > 45$ GeV, and at least 4 jets with $p_T > 20$ GeV. Exactly one identified and isolated lepton is required.

3. Reconstruction of MET

We define $\vec{\cancel{E}}_T$ as the imbalance in the transverse momentum of all particles in the final state of proton-proton collisions that interact via the electromagnetic or strong forces. Because of momentum conservation, $\vec{\cancel{E}}_T$ is the transverse momentum that is carried by weakly interacting or non-interacting particles, such as neutrinos. CMS has developed several distinct and complementary algorithms to reconstruct $\vec{\cancel{E}}_T$, already presented in [6]. The $\vec{\cancel{E}}_T$ reconstructed using a particle-flow technique (PF $\vec{\cancel{E}}_T$) is used in the majority of CMS analyses. It is defined as the negative vectorial sum over all PF particles transverse momenta.

In the following sections, we present a comparison of the performance of PF $\vec{\cancel{E}}_T$. In addition, two advanced $\vec{\cancel{E}}_T$ reconstruction algorithms specifically developed to mitigate effects from large numbers of pileup interactions are discussed. In all comparisons the $\vec{\cancel{E}}_T$ is corrected by correcting the p_T of the jets to the particle level p_T using the jet energy corrections, and recalculating the $\vec{\cancel{E}}_T$. In addition to the corrections discussed above, additional corrections to improve the performance of the $\vec{\cancel{E}}_T$ reconstruction are used in the analyses, such as corrections for the residual ϕ -asymmetry observed in $\vec{\cancel{E}}_T$.

4. Measurement of the MET resolution

The performance of the $\vec{\cancel{E}}_T$ reconstruction is assessed using events where an identified Z boson or isolated photon is present. While there is no genuine $\vec{\cancel{E}}_T$ in such events, we can induce it by removing the vector boson from the event reconstruction. Using the well-measured and well-understood vector boson momentum as a reference, we are able to measure the scale and

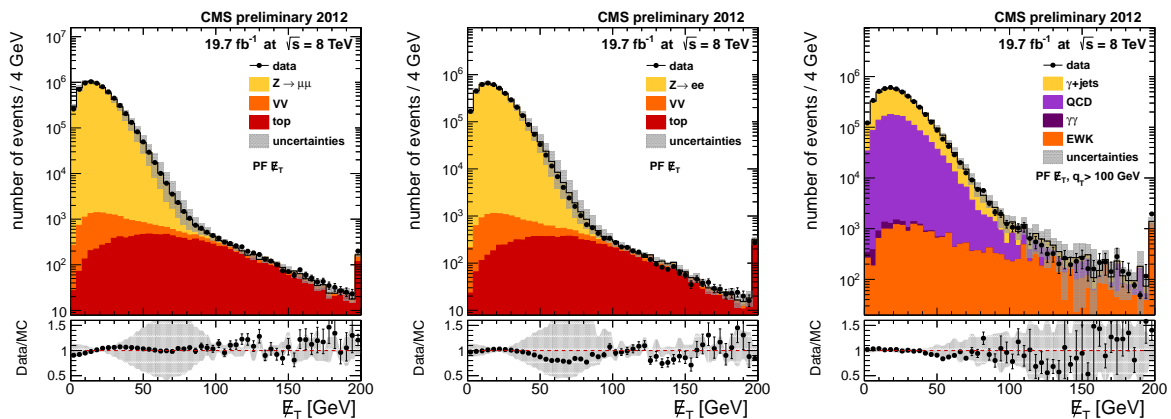


Figure 1. PF E_T^{miss} distribution in events with $Z \rightarrow \mu^+\mu^-$ (left), $Z \rightarrow e^+e^-$ (middle), and photon events (right). The points of the lower section of the plots contain the statistical uncertainties of data and simulation, and the grey error band is the systematic uncertainty on the simulation.

resolution of \vec{E}_T in an event sample with a global hadronic system that is kinematically similar to important Standard Model backgrounds such as $t\bar{t}$ +jets and W +jets.

The PF E_T^{miss} distributions in $Z \rightarrow \mu^+\mu^-$, $Z \rightarrow e^+e^-$, and photon events are presented in Fig. 1. Good agreement of data and simulation is observed in all distributions. Momenta of muons/electrons (photons) originating from Z decays (photons) are reconstructed with resolutions of $\sigma_{p_T}/p_T \sim 1\text{--}4$ (1–3)%, while the energy of jets is reconstructed with resolutions of typically $\sigma_E/E \sim 10\text{--}15\%$. Thus the \vec{E}_T resolution in Z or γ + jets events is dominated by the resolution with which the hadronic activity in the event is reconstructed.

Denoting the vector boson momentum in the transverse plane by \vec{q}_T , and the hadronic recoil, defined as the vectorial sum of the transverse momenta of all particles except the vector boson (or its decay products, in the case of Z bosons), is \vec{u}_T . Momentum conservation in the transverse plane requires $\vec{q}_T + \vec{u}_T + \vec{E}_T = 0$.

The presence of a well measured Z boson or photon provides both a momentum scale, $q_T \equiv |\vec{q}_T|$, and a unique event axis, along the unit vector \hat{q}_T . The hadronic recoil can be projected onto this axis, yielding two signed components, parallel (u_{\parallel}) and perpendicular (u_{\perp}) to the event axis. Since $u_{\parallel} \equiv \vec{u}_T \cdot \hat{q}_T$, and the observed hadronic system is usually in the opposite hemisphere from the boson, u_{\parallel} is typically negative. The scalar quantity $-\langle u_{\parallel} \rangle / q_T$ is referred as the \vec{E}_T response, and the distribution of $-\langle u_{\parallel} \rangle / q_T$ versus q_T as a response curve.

The \vec{E}_T energy resolution is assessed with a parametrization of the $u_{\parallel} + q_T$ and u_{\perp} distributions by a Voigtian function, defined by the convolution of a Breit-Wigner (BW) distribution and a Gaussian (G) distribution:

The resolution curves, $\sigma(u_{\parallel})$ and $\sigma(u_{\perp})$ versus q_T , are shown in Fig. 2. The resolution increases with increasing q_T , and the data and simulation curves are in reasonable agreement for each channel. Figure 3 shows the resolution curves $\sigma(u_{\parallel})$ and $\sigma(u_{\perp})$ versus the number of primary vertices N_{vtx} , for both Z channels and the γ + jets channel. The offset of the curve is related to the resolution in Z or γ + jets events without pileup and the dependence with respect to N_{vtx} indicates how much the pileup degrades the \vec{E}_T resolution. For each additional pileup interaction, the PF \vec{E}_T resolution is degraded by around 3.4 GeV in quadrature.

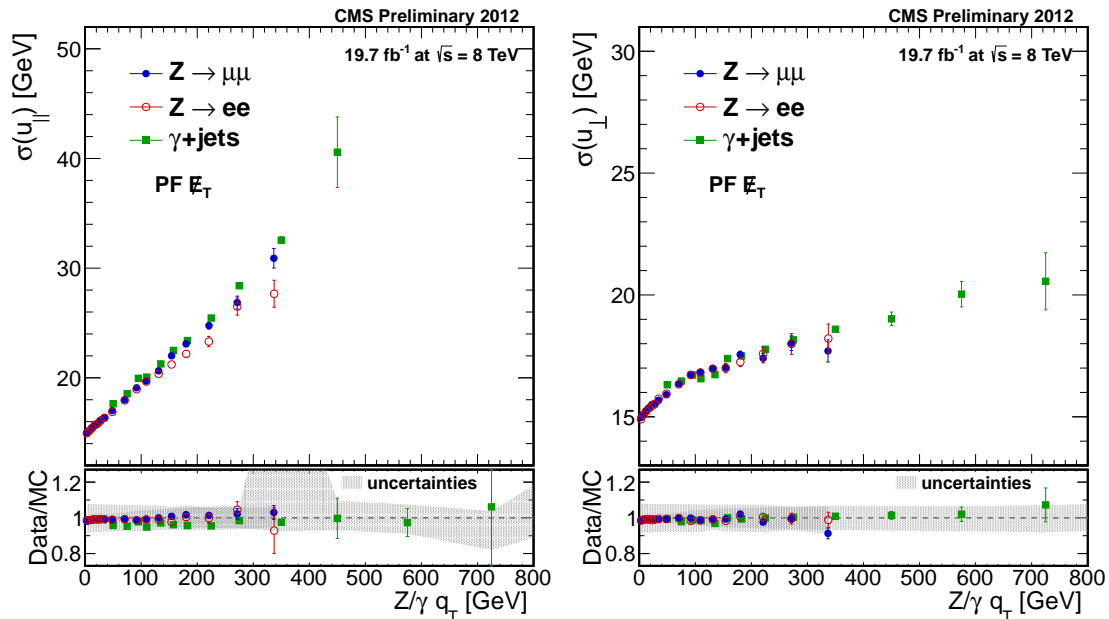


Figure 2. Resolution curves of the parallel recoil component (left) and perpendicular recoil component (right) versus $Z/\gamma q_T$ for PF \vec{E}_T for events with Z and γ . Results are shown for $Z \rightarrow \mu^+\mu^-$ events (full blue circles), $Z \rightarrow e^+e^-$ events (open red circles), and photon events (full green squares). The upper frame of each figure shows the response in data; the lower frame shows the ratio of data to simulation. The q_T value for each point is determined based on the average q_T value in data contributing to each point.

5. Pileup-mitigated MET

Since the vast majority of pileup interactions do not have significant \vec{E}_T and the average value of \vec{E}_T projected in any direction is zero, the effect on \vec{E}_T response from pileup interactions is small. However, as shown in the previous section, pileup interactions have a considerable effect on the \vec{E}_T resolution. In events where the recoil p_T is small and the instantaneous luminosity is around the mean value of 2012 data taking, which corresponds to approximately 20 pileup interactions, the contribution to the \vec{E}_T resolution from pileup interactions is larger than the contribution from the hadronic recoil.

CMS Collaboration developed algorithms to reduce the effect of pileup interactions on \vec{E}_T reconstruction, hereafter referred to as the “No-PU PF E_T^{miss} ” and “MVA PF E_T^{miss} ” algorithms. These algorithms are based on dividing each event into two components: particles that are likely to originate from the primary hard-scattering pp interaction (HS particles) and particles that are likely to originate from pileup interactions (PU particles). More details on the details of the algorithms are given in Ref. [7].

The resolution distributions as a function of N_{vtx} are shown in Fig. 3 and includes also as a reference the standard PF \vec{E}_T algorithm. Significantly reduced dependence of the resolution on pileup interactions in both data and MC simulation. This reduced pileup dependence can significantly increase the sensitivity of searches for new physics. As an example, the sensitivity of the search for the Higgs boson decaying into tau pairs is improved by $\sim 20\%$ thanks to its use of the MVA PF E_T^{miss} [8].

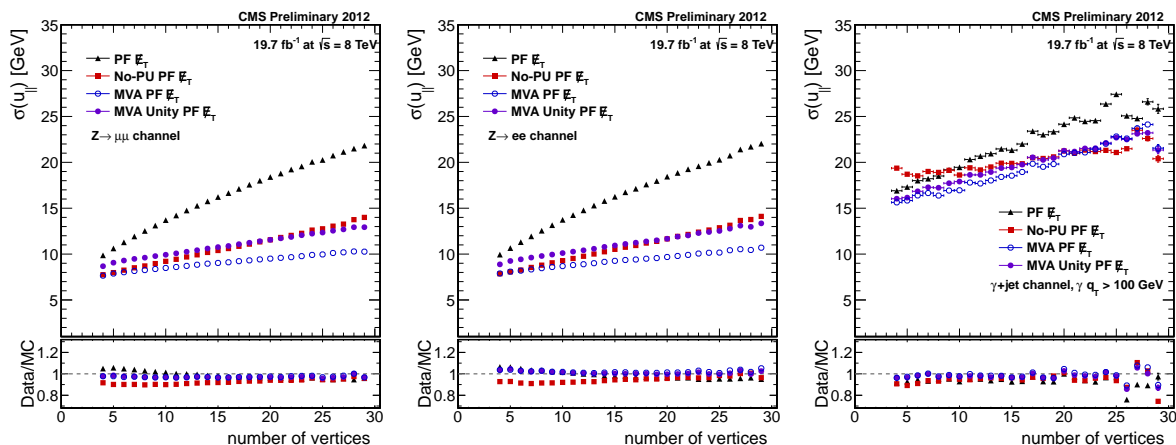


Figure 3. Parallel resolution as a function of the number of reconstructed vertices for PF \vec{E}_T (black triangles), No-PU PF \vec{E}_T (red squares), MVA PF \vec{E}_T (blue open circles), and MVA Unity PF \vec{E}_T (violet full circles) in $Z \rightarrow \mu^+\mu^-$ (left), $Z \rightarrow e^+e^-$ (middle) and $\gamma + \text{jets}$ events (right).

6. MET Significance

The ability to distinguish between events with spurious \vec{E}_T and those with genuine \vec{E}_T is important for analyses using missing transverse energy variables. Fake \vec{E}_T may arise from object misreconstruction, finite detector resolution, or detector noise. To help identify such events, we have developed a missing transverse energy significance variable, which we will denote by " \vec{E}_T Significance", or simply \mathcal{S} . On an event-by-event basis, the Significance evaluates the probability that the observed \vec{E}_T is inconsistent with a null hypothesis $\vec{E}_T = 0$, given the full event composition and resolution functions for each object in the event. A high value of \mathcal{S} is an indication that the \vec{E}_T observed in the event is not well explained by resolution smearing alone, suggesting that the event may contain unseen objects such as neutrinos or more exotic weakly interacting particles. A detailed description and definition of the Significance is given in [6].

The distributions of the \vec{E}_T Significance are shown in Figs. 4 in data and simulation for both the $W \rightarrow e\nu$ and semi-leptonic $t\bar{t}$ channels. Some interesting features are apparent in the composition of simulation events in the Significance spectra. In the $W \rightarrow e\nu$ channel, events arising from zero true \vec{E}_T physics channels, such as QCD and Drell-Yan events, are mostly found at low values of Significance compared to the broad distribution of nonzero- \vec{E}_T events. The semi-leptonic $t\bar{t}$ channel has a significant nonzero- \vec{E}_T background stemming from dileptonic $t\bar{t}$ decays. The dileptonic $t\bar{t}$ spectrum falls more slowly than the semi-leptonic $t\bar{t}$ signal as we approach the tail region of \mathcal{S} .

In the $W \rightarrow e\nu$ channel, there is a performance benefit in using \vec{E}_T Significance, when compared to simpler background-discrimination variables such as \vec{E}_T alone or the approximate Significance variable $\vec{E}_T/\sqrt{\sum E_T}$. For example, choosing a working point with 50% signal efficiency yields a background efficiency of 8.2% using \vec{E}_T , 5.1% using $\vec{E}_T/\sqrt{\sum E_T}$, and 4.0% using the Significance as a cut variable. In the semi-leptonic $t\bar{t}$ channel, \mathcal{S} provides discrimination that is comparable to \vec{E}_T and $\vec{E}_T/\sqrt{\sum E_T}$. This reflects the fact that \mathcal{S} is optimized for discriminating events which satisfy the null hypothesis ($\vec{e} = 0$) from those that do not. In the case of semi-leptonic $t\bar{t}$, the dominant background contribution comes from dileptonic $t\bar{t}$ decays with large, real, \vec{E}_T .

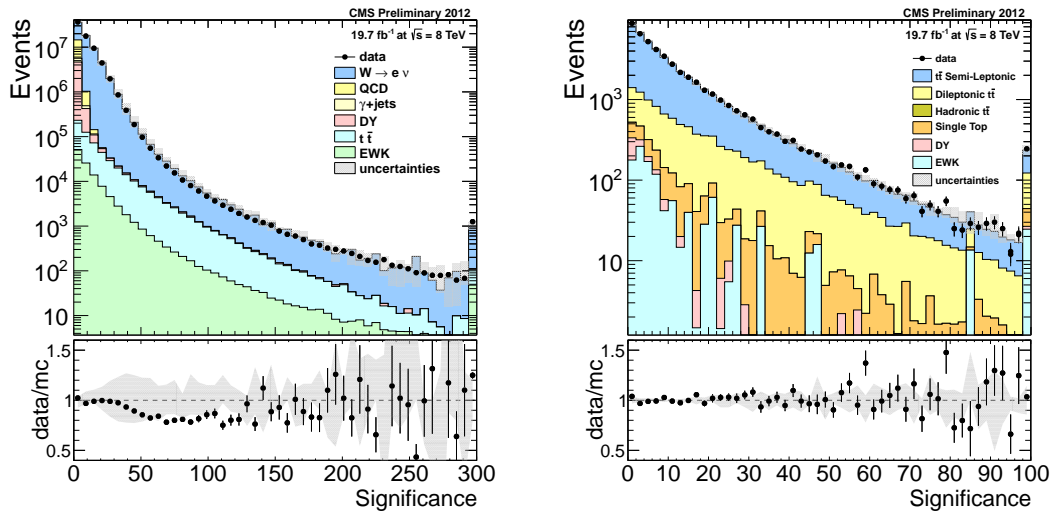


Figure 4. Distribution of \vec{E}_T Significance in the (Left) $W \rightarrow e\nu$ and (Right) $t\bar{t}$ channels.

7. Summary

The performance of \vec{E}_T reconstruction algorithms has been studied using data collected in 8 TeV pp collisions with the CMS detector at the LHC. The performance of the \vec{E}_T reconstruction algorithms is found to be well reproduced by the MC simulation. Pileup interactions are found to degrade the PF \vec{E}_T resolution by 3.4 GeV in quadrature per additional pileup interaction. The performance of advanced \vec{E}_T reconstruction algorithms developed to cope with large numbers of pileup interactions was also been studied, and shows a significantly reduced dependence on pileup interactions.

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